PERGAMON

Atmospheric Environment 34 (2000) 1575–1581

ATMOSPHERIC
ENVIRONMENT

www.elsevier.com/locate/atmosenv

Lycopodium spore impacts onto surfaces

X. Li, P.F. Dunn*, R.M. Brach

Particle Dynamics Laboratory, Department of Aerospace and Mechanical Engineering, University of Notre Dame,
Notre Dame, IN 46556, USA

Received 18 June 1999; received in revised form 2 September 1999; accepted 2 September 1999

Abstract

Experiments on oblique impact of *Lycopodium* spores with dry surfaces in the presence of adhesion were carried out. The experimental results are compared with those of stainless steel microsphere impact onto the same types of substrate surfaces. Three parameters are analyzed, the coefficient of restitution, the impulse ratio and the normalized kinetic energy loss and are used to represent the impact results. The comparisons show that the complex surface profile of a spore has a remarkable effect on impact response. The conjunction of the roughness of both the microparticle and the substrate make the impact mechanics even more complicated. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Restitution coefficient; Impulse ratio; Oblique impact; Surface roughness; Spore surface impacts

1. Introduction

Bioaerosol deposition onto surfaces is a problem with far-reaching applications. Knowledge of the deposition mechanism will help us understand more about the issues such as air pollination of plants and the so-called "office syndrome". It has been known for a while that surface geometry has a significant effect on the impact response for microparticles (Paw, 1983; Aylor and Ferrandino, 1985; Dunn et al., 1996). In this paper, experimental results of individual *Lycopodium* spore oblique impacts onto ultra-smooth and commercial construction material surfaces in a vacuum are reported. These results are compared with those obtained from stainless steel microsphere impact with the same types of surfaces to examine the effect of microparticle surface roughness.

The air in almost all indoor environments contains fungal and plant spores. Environmental factors that influence indoor bioaerosol concentrations include outdoor concentrations, the type and rate of ventilation, filtration and indoor moisture levels. In spaces primarily ventilated through open windows and doors, outdoor air with its spores readily enters, and the indoor bioaerosol reflects that of the outdoors. Even when doors and windows are closed, at wind speeds greater than 1 mph, bioaerosols from the outside air can penetrate indoors through tiny cracks around windows, doors, and walls (Muilenberg, 1995).

Indoor bioaerosols are removed from air by a number of means, including sedimentation, impaction, and diffusion to surfaces. Impaction is a major consideration with larger particles (diameter $> 10\ \mu m$) and is of less importance for small particles. Particle removal efficiency is also related to the type of impaction surface and particle size, stickiness (wetness), electrostatic charge, and hydrophobicity, etc. Muilenberg (1995) pointed out that when a particle makes initial contact with a surface, it is not only air turbulence and physical disturbance that influence if it will adhere or be reaerosolized, but also moisture, hydrophobic interactions, electrical attraction, and physical configuration. These factors include the surface composition of the particle and the ability of the potentially adhering particle and/or landing surface to chemically recognize each other.

Paw (1983) studied the rebound of particles from natural surfaces. He conducted normal (perpendicular) impacts of glass microbeads, ragweed pollen and *Lycopodium* spores (diameter range from 20 to 40 μm) onto natural and artificial surfaces (glass, the leaves of

---

* Correspondence author.
E-mail address: patrick.f.dunn.1@nd.edu (P.F. Dunn)

PII: S1352-2310(99)00411-2

tulip poplar and American elm). The experimental results showed that for each type of particle, the capture velocity was almost the same irrespective of the surface materials. Size effects on the impact response were not studied in his experiments. And in the analysis, he assumed that only the normal incoming velocity component contributed to the rebound.

Aylor and Ferrandino (1985) conducted experiments with ragweed pollen and *Lycopodium* spore impact onto a cylinder. Their observations showed that both the normal and tangential incoming velocity components would determine the impact response. Further, the coefficient of restitution, e, defined as the ratio of rebound total velocity divided by the incoming total velocity, may not be a constant for impacts anywhere on the cylinder. It may increase with the decrease of the incident angle with respect to the substrate surface. Their experimental results also indicated that the substrate surface geometry had a measurable effect on the particle rebound.

Fig. 1 shows the coordinates and variables associated with an oblique impact of a microsphere with a surface. Lower case symbols represent the initial variables and the capital symbols denote the final variables. The mechanics of such an impact in the presence of adhesion are derived in the paper by Brach and Dunn (1995). In their studies, the coefficient of restitution is defined more conventionally by

$$e = -V_n/v_n \tag{1}$$

where the subscript n denotes the normal direction, the symbol V means the rebound velocity and the symbol v the incoming velocity, as shown in Fig. 1. The symbol ω represents the initial rotational velocity and Ω the final rotational velocity. The other parameters used in their analysis to represent impact response are called the impulse ratio, μ, and the normalized kinetic energy loss, TK_L, assuming no mass change during the impacts:

$$\mu = \frac{P_t}{P_n} = \frac{V_t - v_t}{V_n - v_n}, \tag{2}$$

$$\mathrm{TK}_L = \frac{v^2 - V^2}{v^2}, \tag{3}$$

where the subscript t denotes the tangential direction, P_t and P_n are the impulse components in the tangential and normal directions respectively over the entire contact duration. Recent experiments carried out by Dunn et al. (1996) showed that for small angles of incidence, α_i, the substrate surface roughness can bias the experimental results significantly. For α_i less than about 10°, variations ($\phi \neq 0$) in the local surface slope, ϕ, of the order of magnitude of the incident angle will cause values of the "apparent" coefficient of restitution to significantly exceed unity when calculated from the measured velocity component according to Eq. (1). A value greater than 1 is theoretically impossible, of course, because this would require a gain in kinetic energy from the collision. So surface roughness can confound experimental observations, particularly when studying capture. Without knowing the exact local slope where the particle contacts the surface, there seems to be no way to circumvent this issue. It will be seen that irregularities in the microparticle surface (such as with spores) can demonstrate similar effects.

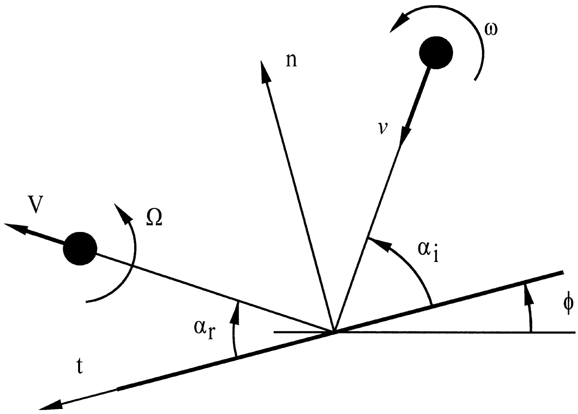

Fig. 1. Coordinates system, velocity components, incident angles and variation in local surface slope.

In the present studies, oblique impact experiments were conducted with *Lycopodium* spore impacts onto silicon and commercial *Formica* surfaces. The total incoming velocities for the silicon and *Formica* surfaces were close but not identical. They averaged around 1.50 m s^{-1} for the silicon case and 1.70 m s^{-1} for the *Formica* case for all incident angles. For comparison, experiments were conducted with smooth stainless steel microspheres (SST76) and the same types of surfaces. The average initial total velocity was about 1.66 m s^{-1} for steel microspheres/silicon surface case and 1.80 m s^{-1} for steel microspheres/*Formica* surface case. The experimental results are compared in the following categories: *Lycopodium* spores and SST76 microspheres onto a silicon surface, *Lycopodium* spores and SST76 microspheres onto a *Formica* surface, and *Lycopodium* spore/silicon and *Lycopodium* spore/*Formica*. The results show that surface roughness of both the microparticle and the substrate surfaces has dramatic effects on impact response.

2. Experimental apparatus and data process

The experimental system is shown schematically in Fig. 2. The impact experiments were carried out under vacuum conditions (10^{-4} Torr) using a system developed by Caylor (1993). The instruments used in the experiments were: a particle trajectory imaging system (PTIS),

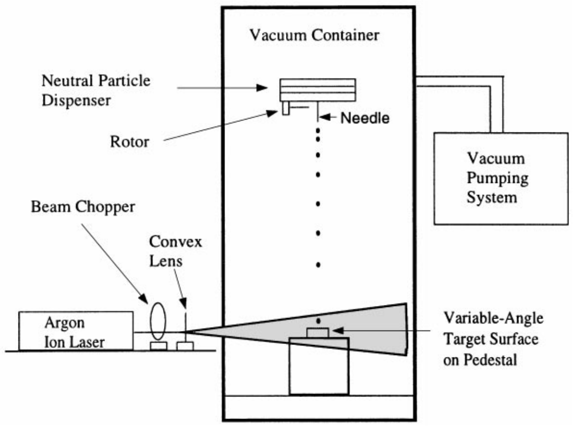

Fig. 2. Schematic of the experimental system: side view.

which is comprised of an Argon ion laser, beam chopper, plano-convex lens, CCD camera and video recorder; a neutral particle dispenser; and a tilted target surface on a pedestal. During an experiment, the microspheres were placed on the dispenser plate. A rotor underneath the plate periodically contacted the plate and vibrated it, causing the microspheres to fall through a hole at its center. To direct the falling particles toward the target surface, a hypodermic needle was connected to the hole.

The PTIS was used to observe and record the particle trajectories. As shown in Fig. 2, an Argon ion laser beam (~ 2 W) passed through a collimator to control beam width to provide a narrow light sheet as possible. The laser beam was then directed through a spinning disk with 10 evenly spaced slots (beam chopper) to produce a pulsed laser beam. Depending on the angular velocity of the disk (measured with a digital stroboscope), the pulsed frequency was varied to obtain a satisfactory track length. The chopped beam went through a plano-convex lens which formed a pulse light sheet aligned in a vertical plane above the target surface. The pulsed laser light sheet illuminated the individual particle intermittently as it approached and rebounded from the surface. The camera was installed approximately 90° to the light sheet. The image was enlarged to get a clear trajectory. The trajectories were recorded on video and processed to obtain the particle's incident and rebound angles and speeds. Based on the frame rate, the field of view, and the strobe frequency, the system could measure particle velocities ranging from ~ 0.1 to $30\ \mathrm{m\ s^{-1}}$.

The velocity components for the normal and tangential directions can be calculated from the angles of incidence and rebound. Based on the rigid body model developed by Brach and Dunn (1995), these velocity components are used to determine three parameters, e, μ and TK_L, that characterize the impact event.

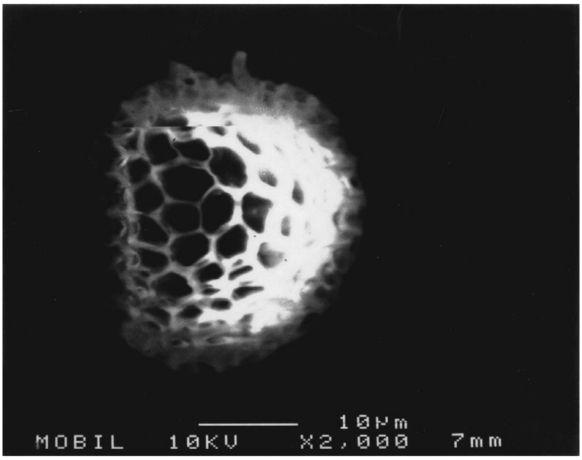

Fig. 3. A SEM picture of a *Lycopodium* spore.

According to the supplier (Duke Scientific), *Lycopodium* spores used in the experiments have diameters ranging from 25 to 35 μm with an unknown distribution. The surface profile of a spore was obtained using a scanning electron microscope (SEM) and is shown in Fig. 3. The stainless steel microspheres (SST76) have diameters ranging from 10 to 110 μm, and the majority are within 64 to 76 μm. The mean diameter is 65.9 μm with a standard deviation of 15.8 μm. Diameter information was taken using phase Doppler particle analyzer (PDPA). Surfaces of steel microspheres are visually smooth based on SEM images.

The silicon substrate, a.k.a the "smooth" surface, was specially prepared from a [1, 0, 0] plane silicon crystal wafer. An atomic force microscope scan of the surface verified that the surface was molecularly smooth (the surface asperity height standard deviation is approximately 10 Å in a scan length of 80 μm). The commercial Formica surface, a.k.a the "rough" surface, was analyzed using a surface profilometer. The standard deviation of the surface heights was about 45 kÅ in a scan length of 4 mm. More detailed information on the surface characteristics is presented in Li (1999).

Uncertainties in measured values of the velocity and angle from video images arise from the variations in measuring distance, angles, and strobe frequency. These variations change with the incident angle and combine to yield uncertainties in velocity components and incoming and rebounding angles. Uncertainties from an error analysis for final results as e, μ and TK_L are illustrated throughout this paper with 95% confidence bands plotted as error bars. The sample mean value of each quantity is determined first by computing the quantity's value for each individual impact event. Then, its mean value is computed as the ensemble average of all the events detected (about 40 events for each point).

3. Experimental results and discussions

3.1. Microparticle impact onto a silicon surface

Experimental results of *Lycopodium* spore and SST76 microsphere impact onto silicon surfaces are plotted in Fig. 4. For the SST76 microspheres, the coefficient of restitution is approximately constant from 90 (normal) down to 10°. Then, the value of e decreases with decreasing incident angle. When the incident angle α_i decreases from 90 to 55°, the magnitude of the coefficient of restitution for the *Lycopodium* spores and the SST76 microspheres is approximately the same. The value is close to a constant of 0.70. It seems that the microparticle material difference and the surface irregularities of *Lycopodium* spore have nothing to do with the impact response in this region. Below this region, the experimental results for these two cases show some differences. The coefficient of restitution for the *Lycopodium* spore decreases from about 0.70 to less than 0.55 when the incident angle are within 48 to 38°. When a microparticle has a smaller diameter, in the presence of adhesion, the coefficient of restitution will decrease more sharply when the normal velocity component becomes smaller (Li et al., 1999). Paw (1983) estimated that for *Lycopodium* spores of 20 to 40 μm diameter, the capture velocity was $1.30\,\mathrm{m\,s^{-1}}$ when impacting onto American elm leaves. For the experiments shown in Fig. 4, the incoming normal velocity components are computed by $v_n = v \sin \alpha_i$. Where α_i is between 48 to 38°, values of v_n are about 1.10 to $0.90\,\mathrm{m\,s^{-1}}$. So a decrease is expected of the coefficient of restitution due to effects of adhesion. When the angles of incidence and the normal incoming velocity component decrease, *e* should continue to decrease (see the open squares for SST76 microsphere), but it does not for *Lycopodium* spores (solid squares). When incident angles are lower ($< 38°$) and decreasing, the coefficient of restitution for *Lycopodium* spores increases. Behavior similar to this has been observed under different conditions in the oblique impact study by Dunn et al. (1996) where microspheres were smooth and surfaces were rough. Their results show that substrate roughness will cause such increase of the coefficient of restitution. However, such an increase in the values of *e* is not due to the physical process but due to variations in local slope ϕ. It may be possible that the surface geometry of a *Lycopodium* spore causes the increase of the coefficient of restitution seen in Fig. 4. Other factors, such as collisions with simultaneous multiple contact points and/or non-central collisions due to irregular *Lycopodium* spore surface profile, may also be contributors for the increase.

The change in the normal velocity component during impact is generally determined by the elastic and dissipative properties of the materials and of adhesion. On the other hand, the change in tangential velocities due to impact is due less to elastic properties but more due to the effects of friction. Consequently, the coefficient of restitution represents the "normal" physical process whereas the impulse ratio, μ, represents a different, tangential, physical process.

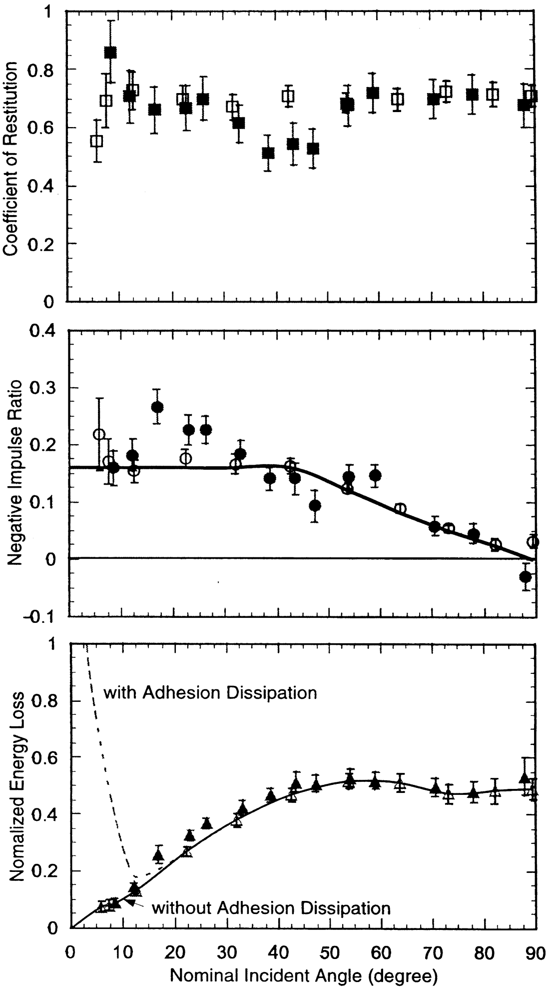

Fig. 4. Comparisons of the impact results for *Lycopodium* spore and SST76 microsphere onto a silicon surface (open symbols: SST76 microsphere; solid symbols: *Lycopodium* spore. Solid and dashed curves are from theoretical models).

Comparisons of the trends of the impulse ratio with changing incident angle also show the effect of microparticle surface geometry, friction and initial conditions. Note that for convenience, negative values of μ are plotted as positive in all the following figures containing the impulse ratio. The solid line in the middle of Fig. 4 is the result of applying the rigid body model presented by Brach and Dunn (1995) to the SST76 microsphere case. In this model, the region of increasing impulse ratio (from 90° down to about 40°) is called the "rolling region", where a particle is rolling without sliding when it leaves the surface. The relatively constant impulse ratio region (below 40°) is called the "sliding region", where a particle slides throughout the duration of contact. The constant value may be interpreted as Coulomb's coefficient of friction. The impulse ratio from SST76 microspheres oblique impacts with silicon surface follow this behavior reasonably well. However, below about 10°, the measured impulse ratio does not remain constant but increases in the SST76/silicon experiments. This is because when the initial normal momentum is very small, adhesion attracts the microparticle toward the surface allowing friction to more effectively decrease the tangential momentum and results in an increasing P_t. Consequently, μ (see Eq. (2)) becomes large.

The impulse ratio for the *Lycopodium* spores behaves somewhat differently. It increases when the incident angle decreases from 90° to about 60°. Below 60°, it does not seem to develop any consistent trends. Inconsistent impulse ratios indicate inconsistent tangential impulses and to some extent reflect the inconsistent normal dissipation (demonstrated by the restitution, e).

The comparison of the measured normalized kinetic energy loss shows no substantial difference between these two cases. It seems that the difference of the type of microparticles has no effect on the normalized kinetic energy loss under the present experimental conditions. From this data, it seems that to examine the effects of materials, surface geometry, etc., on the impact response, it is better to examine the parameters e and μ. Yet, TK_L is related to e and μ from mechanics.

From the rigid body impact model (Brach and Dunn, 1995), the normalized kinetic energy loss TK_L is shown to be

$$TK_L = [1 - e^2 + 2\mu(1+e)\eta - \mu^2(1+e)^2]/(1+\eta^2) \quad (4)$$

in which it is assumed that there is no microsphere initial spin, and where $\eta = v_t/v_n = \tan^{-1}\alpha_i$. In absence of adhesion, when α_i is small, μ is roughly constant, e approaches one and η grows large. TK_L tends toward to zero (it will never be zero exactly unless there is no adhesion dissipation and material dissipation). When adhesion is present, however, as the initial normal velocity becomes small, the effects of adhesion become significant. As shown by the theoretical dashed curve in Fig. 4, adhesion causes the restitution coefficient to tend toward zero (with decreasing α_i), leading to capture. The experimental values of TK_L below about 10° do demonstrate a slight tendency to this effect for steel microspheres. In general, however, the measurements do not conclusively demonstrate the tendency to capture for *Lycopodium* spores.

When the incident angle is large and the tangential velocity component is negligibly smaller than the normal component, μ tends toward zero, the normalized kinetic energy loss approaches $TK_L \sim (1 - e^2)$. As a result, even a small difference of e will have a significance in TK_L, which will be shown in the following section. But for those experiments in Fig. 4, because the coefficient of restitution is almost the same for incident angles from 90 to 60°, there is little difference in TK_L.

3.2. Microparticle impact onto a Formica surface

Oblique impact experiments of *Lycopodium* spores and SST76 microspheres onto a commercial *Formica* surface were also conducted. A *Formica* surface is much more irregular than a silicon surface. The experimental results are plotted in Fig. 5. From the figure of the coefficient of restitution, it can be seen that for the same incident angles, the open squares (SST76/*Formica*)

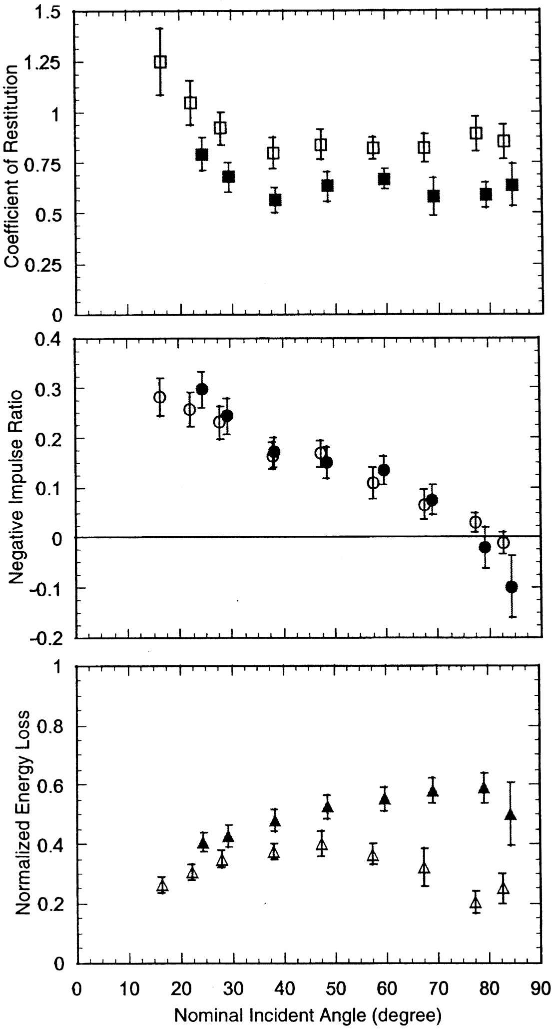

Fig. 5. Comparisons of the impact results for *Lycopodium* spore and SST76 microsphere onto a *Formica* surface (open symbols: SST76 microsphere; solid symbols: *Lycopodium* spore).

are significantly higher than the solid ones (spores/*Formica*), although the trends are the same. The coefficient of restitution increases with decreasing incident angle for both cases. The measured values of the coefficient of restitution for the SST76 case exceed unity when the incident angle is less than 20°. As discussed earlier, this can be attributed to the variations in the local values of the surface slope, ϕ. The increase of the coefficient of restitution with decreasing incident angle is more a measurement phenomenon and does not necessarily mean no particles were captured in the experiments. Under the present experimental setup, only those impacts with a rebound were observed and analyzed. A statistical model of *Lycopodium* spore oblique impact onto surfaces with random variations is considered in Li (1999) and covers this in more depth.

The impulse ratio for these two cases is approximately the same (shown in the middle of Fig. 5). The surface roughness of *Formica* may be the dominant contributor to friction. Thus, the difference of the microparticle surface geometry between a *Lycopodium* spore and a SST76 microsphere appears not to affect the tangential resistance and consequent impulse.

The normalized kinetic energy loss showed that the impact of *Lycopodium* spores onto *Formica* yields higher energy loss, especially at higher incident angles. It is not surprising because it has already seen that the *Lycopodium* spore case gives lower coefficient of restitution. From Eq. (4), at high incident angles, $\mathrm{TK}_L \sim (1 - e^2)$ and the normalized kinetic energy loss for *Lycopodium* spore should be higher. Below $\alpha_i < 45°$, the difference of TK_L between these two cases becomes smaller although still apparent.

3.3. *Lycopodium spores impact onto silicon and Formica surfaces*

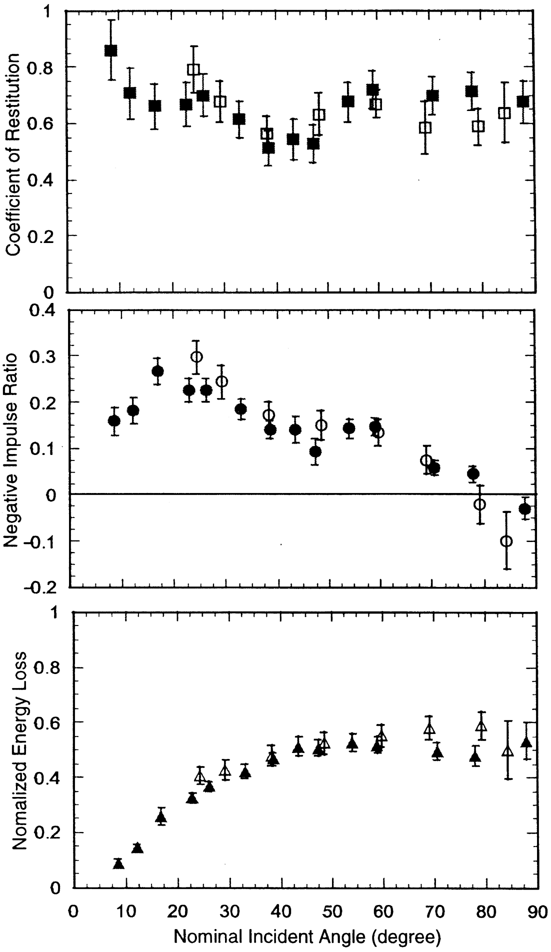

Fig. 6. Comparisons of the impact results for *Lycopodium* spore onto *Formica* and silicon surfaces (solid symbols: silicon surface; open symbols: *Formica* surface).

Comparisons of the experimental results of *Lycopodium* spores onto a silicon surface and onto a *Formica* surface are shown in Fig. 6. It can be seen that *Lycopodium* spore impact onto silicon surface yields a higher coefficient of restitution at high incident angles (from 90° down to 60°). At higher angles of incidence, the difference between the *Formica* surface and the silicon surface causes a remarkable difference in the coefficient of restitution. This may be explained by the conjunction of factors, such as the substrate and particle surface roughness and the difference in material properties between *Formica* and silicon. As a result, the *Formica* surface gives slightly higher values of the coefficient of restitution (at incident angles from 50° down to 20°).

The impulse ratio changing with the incident angle also shows the effect due to conjunction of substrate and particle surface geometry. At higher incident angles (90° down to 60°), the increasing of impulse ratio showed approximately the same trend for these two cases. Different from those trends described in Section 3.1 for the *Lycopodium* spore/silicon case, the impulse ratio increases consistently when incident angle decreases from 60° to about 25° for the *Formica* surface case. The combination of surface roughness of *Formica* substrate and *Lycopodium* spore has a moderate effect on the impulse ratio. The negative values of μ for high angles of incidence (recall that signs are reversed for plotting) can be explained by microparticle's non-zero initial angular velocity, ω (Li, 1999).

Comparison of the normalized kinetic energy loss suggests that at higher incident angles (90° down to 60°), the difference of the coefficient of restitution results in a difference in normalized kinetic energy loss. Below this region (60° down to 25°), *Lycopodium* spores impaction with *Formica* surface yielded a slightly higher TK_L. There is no trend for the energy loss to increase as $\alpha_i \rightarrow 0$. The surface roughness seems to mask any tendency for particles to be captured in these experiments.

Bioaerosol impact mechanics itself is very complex. Many questions, such as how the irregular surface geometry of a spore will affect the adhesion force and the friction force in case of oblique impact, cannot be answered definitely yet. Understanding of the mechanics of *Lycopodium* spore impact onto substrate surfaces needs more research about the fundamentals of bio-adhesion force, surface physics and chemistry, and the characterization of surface geometry.

4. Conclusions

Experimental impacts of stainless steel microspheres and *Lycopodium* spores onto silicon and Formica surfaces shows that the coefficient of restitution value is significantly biased by variations in surface geometry at low angles of incidence. As the initial normal velocity becomes very small (as α becomes very small), the effects of adhesion leading toward the condition of capture are expected. However, at small angles surface roughness causes measured values of restitution to increase. So, for oblique collisions, surface roughness can frustrate the measurement of capture.

The comparisons of the impact results for *Lycopodium* spores and SST76 microspheres onto a silicon surface demonstrate the effect of microparticle surface roughness on the impact response. The differences in the trends of the coefficient of restitution and the impulse ratio demonstrate the influence of microparticle surface profile. The impact results of *Lycopodium* spores with a *Formica* surface have differences from those of stainless steel microspheres with the same type of *Formica* surface. The combined surface roughness of the microparticle and the surface make the impact mechanics more complicated. *Lycopodium* spore impact onto a silicon and onto a *Formica* surface also show the complex consequences of the conjunction of microparticle and substrate surface geometry effects. The rigid body model presented by Brach and Dunn (1995) helps us obtain a better understanding of the experimental results.

Acknowledgements

The research described in this article was supported in part by the Center for Indoor Air Research (Contract No. 96-06) and in part by the Electric Power Research Institute (Contract No. RP 8034-03).

References

Aylor, D.E., Ferrandino, F.J., 1985. Rebound of pollen and spores during deposition on cylinders by inertial impaction. Atmospheric Environment 19, 803–806.

Brach, R.M., Dunn, P.F., 1995. Macrodynamics of microparticles. Aerosol Science and Technology 23, 51–71.

Caylor, M.J., 1993. The impact of electrically charged microspheres with planar surfaces under vacuum conditions. Ph.D. Dissertation, University of Notre Dame.

Dunn, P.F., Brach, R.M., Janson, G.G., 1996. Surface-contact mechanics during oblique impact of microspheres with planar surfaces. Aerosol Science and Technology 25, 445–465.

Li, X., 1999. Microparticle impact onto surfaces. Ph.D. Dissertation, University of Notre Dame, July.

Li, X., Dunn, P.F., Brach, R.M., 1999. Experimental and numerical studies on the normal impact of microspheres with surfaces. Journal of Aerosol Science 30 (4), 439–449.

Muilenberg, M.L., 1995. The outdoor aerosol. In: Burge, H.A. (Ed.), Bioaerosols. Lewis Publishers, Boca Raton, pp. 163–204.

Paw, U.K.T., 1983. The rebound of particles from natural surfaces. Journal of Colloid and Interface Science 93, 442–452.